Outcome errors are not necessary for learning orthopedic bone drilling

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Background: When learning orthopedic bone drilling, a surgical trainee relies on internally generated and externally provided feedback. The quality and type of feedback often varies in the clinical environment, thus affecting skill acquisition. We investigated the effect of feedback on technical error (plunging) when novice surgical trainees learned bone drilling.

Methods: Medical students (n = 22) and experienced postgraduate surgical residents (n = 4) drilled bicortical holes in a lamb femur under 1 of 3 feedback conditions: no feedback, self-generated feedback and externally generated feedback. Novices performed a retention test (10 bicortical holes) 1 week after the initial training. We measured plunge depth, the clinically relevant outcome, using computer-assisted methods.

Results: During the initial experiment, the plunges of novices who were exposed to external feedback were similar to those of residents in the experienced group. Novices in the self-generated feedback group plunged more than those in the external feedback group or those in the experienced group (p = 0.002). All novices plunged similarly on the retention test, a measure of true skill learning.

Conclusion: When learning bicortical bone drilling, feedback related to plunging is not necessary to achieve a competent level of performance. In addition, although external feedback facilitates the achievement of better outcomes, it does not improve learning. It is suggested that to minimize plunging, trainees should learn how to optimize their drilling through the bone rather than how to prevent the plunge.

Contexte : L'apprentissage du forage orthopédique osseux s'appuie sur des réactions d'origine interne et une rétroaction externe. La qualité et le type des réactions varient souvent dans l'environnement clinique, ce qui a une incidence sur l'acquisition des compétences. Nous avons étudié l'effet de la rétroaction au sujet d'une erreur technique (la percée) durant l'apprentissage du forage osseux par des novices.

Méthodes : Des étudiants en médecine (n = 22) et des résidents postdoctoraux en chirurgie expérimentés (n = 4) ont foré des trous bicorticaux dans un fémur d'agneau dans 1 de 3 conditions : aucune rétroaction, réaction d'origine interne et rétroaction externe. Les novices ont pratiqué un test de rétention (10 trous bicorticaux) 1 semaine après avoir reçu leur première formation. Nous avons mesuré le résultat cliniquement pertinent, soit la percée, par des méthodes informatisées.

Résultats : Au cours de l'expérience initiale, la profondeur du forage effectué par des novices exposés à une rétroaction externe ressemblait à celle du forage pratiqué par des résidents expérimentés. Les novices du groupe dont la réaction était d'origine interne ont foré plus profondément que ceux du groupe où les commentaires provenaient de l'extérieur ou ceux du groupe des participants expérimentés (p = 0,002). Tous les novices ont foré un trou de la même profondeur lors du test de rétention, mesure de l'acquisition réelle de la technique.

Conclusion : Dans l'apprentissage du forage de trous bicorticaux dans un os, il n'est pas nécessaire de recevoir des commentaires sur la profondeur pour acquérir un bon niveau de compétence. En outre, même si une rétroaction externe aide à produire de meilleurs résultats, elle n'améliore pas l'apprentissage. On indique que pour minimiser la profondeur, les stagiaires devraient apprendre à optimiser leur forage dans l'os au lieu d'apprendre à éviter la percée.

There is a commonly used phrase, "to err is human," but is error necessary or even acceptable in surgical training? During a bicortical bone drilling task, the goal of the surgeon is to drill completely through the width of the bone and stop advancing the drill bit before it plunges into the soft tissues on the other side of the bone. Minimizing the plunge is crucial for successful execution of the skill and has clear clinical importance. Therefore plunging, or the amount of drill bit penetration into the underlying soft tissues, may be considered a form of clinical and technical error. Typically, this most fundamental of orthopedic skills is learned in the operating room (OR) on live patients, where error may have detrimental consequences in the form of soft tissue, vascular or neurologic injury.

The traditional approach to the technical training of surgical residents has been that of Halsted,[1] who emphasized graded responsibility in the context of an apprenticeship model. However, this model has come under scrutiny in recent years as a result of heightened concerns over patient safety, OR budgetary constraints that limit teaching opportunities, advanced surgical innovations (e.g., minimally invasive surgery) and limitations to resident hours.[2–4] Consequently, there has been a push to move a portion of basic technical skills training from the OR to bench-top model settings in surgical skills facilities. By using these new settings, time spent in the OR could potentially be focused on refining and building upon the basic skills already learned in the simulated environment.[5]

One major theoretical advantage to practising outside of the OR is the ability to commit error without negative consequences. It is believed that motor learning, which includes learning isolated surgical technical skills, is best achieved when the learner is free to commit errors.[3,6] Another theoretical advantage is that bench model training provides trainees with additional feedback, often termed "extrinsic" or "augmented" feedback, related to their performance or the outcome of the task. Such feedback originates from an external source such as a videotape of the task or an expert evaluator. When extrinsic feedback is not available, the learner relies only on intrinsic feedback (i.e., self-perceived information about the performance or the final outcome). Intrinsic feedback is provided by the learner's own sensory systems (visual, auditory, proprioceptive, vestibular and cutaneous). Extrinsic feedback facilitates learning and allows a trainee to attain the skill more effectively. However, literature suggests that gains attributable to extrinsic feedback are often transient, specific to training and do not result in improved performance or outcome when tested on retention or transfer tests.[7] In this theoretical view, learning technical skills in the OR by following Halsted's model of "see one, do one, teach one" is suboptimal, although arguably it could be excellent for the acquisition of higher order surgical decision-making processes. Bench model training available in laboratory settings may offer a valuable adjunct to learning basic surgical skills in the OR.

The purpose of our study was to investigate the advantage of learning a bicortical bone drilling skill on a bench model with the freedom to commit clinical error in the form of plunging. We examined outcomes both during acquisition and in the context of retention of this technical skill. We hypothesized that

- repeated bench-model practice of bicortical bone drilling would result in improved proficiency;
- if internally generated information about error in the form of plunging is necessary to the learning process, then preventing the trainees from plunging would be detrimental to their ultimate outcomes on a retention test considered to be indicative of final learning;[8] and
- augmented feedback would result in improved initial outcome but may not translate to improvements in final learning.

Methods

We tested our hypotheses in a 2-part experiment. In the first part of the experiment, the acquisition phase, novice trainees repeatedly practised the bicortical bone drilling task while receiving 1 of 3 types of feedback: no feedback, intrinsic and augmented feedback. We assessed their outcomes by measuring the plunge depth in each trial. We used results from this phase to test our hypothesis that repeated bench-model practice of bicortical bone drilling would result in improved proficiency. In the second part of the experiment, the assessment phase, we used a retention test to evaluate the final learning of the bone drilling skill. We tested our remaining 2 hypotheses by comparing the final outcomes of trainees who had received different types of feedback in the acquisition phase. The University Health Network Research Ethics Board approved our study, and all participants provided their informed consent before taking part in the study.

For the novice group, we included second-year medical students with no neurologic disorders and who had not performed the bone drilling skill in the OR. We assigned each person in the novice group a unique participant number, and we used the numbers to randomly assign participants into the 3 experimental subgroups. These groups received different types of feedback about their plunging during the acquisition phase. To prevent participants in the no feedback group from plunging, we placed a physical restraint on the drill bit; thus they received neither intrinsic nor extrinsic feedback about plunging. Participants in the intrinsic feedback group drilled and plunged without any restraint. We did not provide them with any form of external feedback; thus they were exposed only to intrinsic, self-generated feedback about their plunging. Participants in the augmented feedback group also drilled without any physical restraint. In addition to the self-generated intrinsic feedback, they also received augmented feedback in the form of an auditory tone generated every time the drill bit plunged more than 5 mm. We set this error rate based on a pilot study showing that practising surgeons plunge on average 3 (standard deviation 2) mm.[3]

In the experiened group, we included third-year postgraduate surgical trainees, as they had performed this skill in the OR during typical resident rotations, but had not yet reached the required level of expertise. Participants in this group took part only in the acquisition phase of our experiment. We used their data strictly for method validation purposes (construct validity). Trainees in this group drilled under the same conditions as novice participants who were assigned to the intrinsic feedback subgroup.

We used a lamb femur bone model for drilling, because this model provides an acceptable representation of the human radius at a much lower cost than human cadaveric bone. The model consisted of the distal part of a lamb femur, about 20 cm in length. The average cross-sectional area of the bone was constant at about 1.5 cm. Postsacrifice, the bones were placed in a commercial freezer at –23°C for 2–7 days. Twenty-four hours before the experimental session, we placed each bone in a refrigerator to thaw. The bones were not treated with any chemicals. A custom-made bone holder secured the bone to a small force sensor (Gamma F/T; ATI Industrial Automation; 200 Hz sampling frequency and 0.0025 N resolution). Participants used a nitrogen-powered surgical drill (AO Drill Reamer; Hall Series 4, Model 5067 with 100 PSI pressure) equipped with a 3.5-mm Zimmer drill bit (Zimmer Inc.). We placed a position marker on the handle of the drill; we analyzed its movements, and hence the movements of the drill, using an Optotrak 3-dimensional motion analysis system (Northern Digital Inc.; 200 Hz sampling frequency, 0.001 mm spatial resolution and root mean square positional accuracy of 0.1 mm). We calculated plunge depth as the difference between the instantaneous position of the drill when the readings on the force sensor rapidly began to approach zero (i.e., when the last layer of bone was penetrated) and the lowest position of the drill before the direction of progression reversed (i.e., before the drill was pulled out) or progression of the drill stopped. We provided auditory feedback using a custom-designed plane detection device (Sun Innovations). We placed a wide (20-mm) laser beam 5 mm under the lower surface of the bone. The beam was connected to an electrical circuit and an auditory tone generator, such that if the drill bit plunged more than 5 mm the beam was interrupted and the tone was emitted.

We explained the ideal parameters of the bicortical bone drilling procedure to the participants, but we did not allow them to practise before we began the experiment. Trainees stood in front of the experimental apparatus; a footstool was available for them to reach an optimal height for drilling. Each trial began with a participant holding the drill bit about 2 mm above the bone and then drilling downward through the entire thickness of the bone. The trial ended when the bone was traversed by the drill bit. In the acquisition phase, each participant executed 60 trials in a single session. The assessment phase took place in a single session separated from the acquisition phase by a 1-week retention period of no practice. Participants drilled 10 new bicortical holes in a fresh lamb femur bone. The trainees were not prevented from plunging and did not receive augmented feedback at this time. This second phase was a retention test to assess the total amount of learning that had taken place.

We performed statistical analyses using SPSS 13.0 software (SPSS Inc.). The Shapiro–Wilk test revealed that the data were not normally distributed. Consequently, we performed nonparametric tests and planned comparisons to analyze the data. For all analyses, $p < 0.05$ indicated statistical significance.

We divided data on plunge depth from the acquisition phase into trial blocks (6 blocks of 10 trials). We performed a Kruskal–Wallis test for overall comparison of the ranked mean plunge values in the first and last acquisition blocks of the trainees in each group (intrinsic feedback, augmented feedback, experienced). The "no feedback" group did not generate any data for this analysis because trainees in this group did not plunge in the acquisition phase. When the result of the Kruskal–Wallis test was significant, we used a planned comparisons approach to investigate differences in each group's outcomes in the first and last 10 trials, and we used a Mann–Whitney U test for between-group comparisons. We analyzed data from the assessment phase similarly. We computed and ranked mean plunge values for each group. We used a Kruskal–Wallis test to compare these ranked means.

Results

We included 22 participants in the novice group. Of these, 7 participants were randomly assigned to the augmented feedback group, 7 to the intrinsic group and 8 to the no feedback group. We included 4 third-year postgraduate surgical trainees, who formed the experienced group of participants.

We first investigated the effect of repeated practice of the bicortical bone drilling procedure on outcomes during the acquisition phase. The Kruskal–Wallis test revealed a strong effect ($H_5 = 18.40$, $p = 0.002$). Subsequent planned comparisons using the Mann–Whitney U tests showed that, at the beginning of the acquisition phase, the intrinsic feedback group plunged more than the augmented feedback group ($p = 0.028$) and that the augmented feedback group plunged to the same extent as the experienced group ($p = 0.26$). By the end of the acquisition phase, plunging decreased both in the intrinsic feedback group ($p = 0.05$) and in the augmented feedback group ($p = 0.018$), but not in the experienced resident group ($p = 0.56$). During the final 10 practice trials, the augmented feedback group plunged less than the intrinsic feedback group ($p = 0.008$). Overall, this implies that practice is beneficial to the novices but not to the advanced trainees and that augmented feedback improves outcomes during practice.

In the assessment phase we used a delayed (1-week) retention test to assess how well the novice trainees had learned the skill. A Kruskal–Wallis test applied to the outcomes of the 3 groups revealed that there were no differences among these groups on the retention test ($H_2 = 0.136$, $p = 0.93$; Fig. 1). Also, the outcomes of novices on the retention test were not different from the outcomes of the experienced group in the first 10 trials of the acquisition phase, as shown by a nonsignificant Mann–Whitney *U* test ($p = 0.72$). This indicates that all novice groups learned equally well how to prevent plunging, regardless of the type of feedback they had received during skill acquisition. The implication is that preventing trainees from plunging did not impede their ability to learn the bone drilling procedure. Furthermore, the fact that the augmented feedback group performed on par with the others supports our hypothesis that the advantage of extrinsic feedback is only transient.

Discussion

Learning technical surgical skills is an integral and defining component in the training of competent surgeons. The primary facilitator of this process is practice; the old creed "practice makes perfect" is still the foundation of surgical education.[1] However, the science of human motor learning and behaviour shows that the ability to commit error accompanied by proper feedback can also significantly improve learning.[3,7] Although decades of experience in surgical education indicate that the traditional OR training methods are effective, in the age of medico-legal dominance and shrinking resident work hours, novel methods are required to augment learning.[2,8] Because of practical, financial, ethical and theoretical advantages, the simulated bench model training provides the surgical educator with the opportunity to standardize the quality and quantity of hands-on practice, allowing for outcome errors and the use of multimodal feedback to correct them. The purpose of our study was to assess the contributions of bench model–based practice to the development of proficiency on a bicortical bone drilling skill and to investigate the role of error allowance in the form of plunging in the learning process.

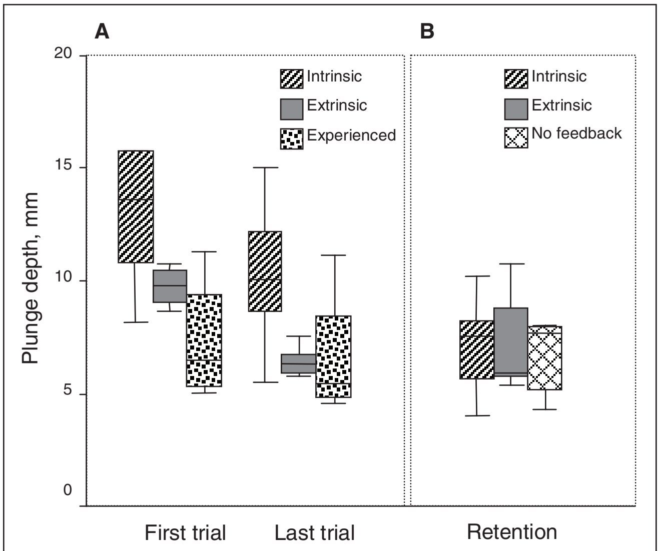

Fig. 1. Median, 95% confidence intervals and ranges depicted as the horizontal line, shaded area and error bars, respectively, are provided for the (**A**) first and last blocks of 10 practice trials in the acquisition phase and (**B**) the retention phase. Note that in the acquisition phase the no feedback group was not included, and in the retention phase the experienced group was not included in our analyses.

Collectively, our results demonstrate that a relatively short practice session on an isolated bench model leads to gains in proficiency on the bicortical bone drilling skill. The initial amount of plunge among medical students decreased by 36%, and by the end of the practice session their plunge depth was similar to that of third-year postgraduate residency trainees. Although the presence of augmented feedback proved to be beneficial to the initial outcomes during the early learning stages, this approach did not lead to significant long-term learning benefits. Most interestingly, our results clearly demonstrate that prevention of error (i.e., plunging) did not have adverse effects on learning or skill retention. In other words, the novices did not need to commit the error to learn how to prevent plunging. This suggests that although the OR-based practice may be disadvantaged by the lower number of repetitions compared with a bench top–based practice, the heavy supervision by faculty and continuous effort by the attending surgeon to prevent commission of errors such as plunging on live patients, does not interfere with the learning process, as suggested in motor learning literature. Overall, despite modern advances in teaching, our findings do not negate the traditional teaching methods in the OR.

Theoretical implications

Our findings can be explained in light of the classical motor learning theory.[7] According to this theory, some form of feedback is required for motor learning to occur.[9] Motor patterns and improvements in movement efficiency can be learned using intrinsic feedback, provided to the performer by the sensory systems as a result of movement. When intrinsic sensory feedback provides enough information to influence the behaviour and lead to learning, augmented feedback is not necessary.[10] Conversely, motor learning can benefit from externally generated augmented feedback if the movement itself does not provide enough intrinsic feedback to influence the behaviour.[6,11] Lastly, if withdrawal of both the intrinsic and augmented sources of feedback about either the performance or the movement outcome does not alter the learning process, then these sources are evidently not required for learning.

Our data show this to be the case: neither withdrawing intrinsic feedback about plunging nor providing augmented feedback affected the outcomes that novice trainees achieved on the retention test. Therefore, we argue that information about the plunge was not necessary for the changes in behaviour that we observed.

There are 2 types of augmented feedback: knowledge of performance, which refers to the movement pattern used to achieve the goal, and knowledge of results, which is outcome- or goal-oriented. In our experiment, an auditory tone warning participants when they plunged too far is an example of feedback augmenting the knowledge of results. Whether knowledge of results or knowledge of performance is more effective at enhancing the learning of a skill is a controversial topic and depends on the nature of the skill in question. We argue that for the particular skill of isolated, bench top–based bicortical bone drilling, knowledge of results in the form of plunge depth is not required for learning. However, it does influence practice performance, as shown by improved performance of novices during the acquisition phase of this experiment. These gains, however, were transient and did not translate into improved outcomes on the retention test. Therefore, it is possible that the trainees learn how to properly drill though the bone, including drilling force application, improvements in the use of feedback to anticipate changes in bone density and adjustment of drill speed, to optimize the drilling actions. Collectively, these are examples of knowledge of performance. Testing the effects of knowledge of performance on clinical outcomes and learning is one of our future research directions.

Practical implications

Orthopedic surgical educators, both those who use bench-top training and those who teach in the OR, should attempt to focus the trainee on the process of drilling, not necessarily on the prevention of the adverse outcome. To achieve best results, the proper understanding of bone anatomy such as cortical arrangement may prove to be beneficial.[5,12] For example, when explaining and correcting the technical performance of drilling, the expert surgeon should address the direction, speed and force applied and the importance of listening to the pitch of the drill as it progresses though the various cortical layers rather than asking the trainee to minimize the plunge depth. Proper understanding of the anatomy of the bicortical bone, with its symmetric arrangement of cortical layers, may help the trainee to map various feedback characteristics (e.g., the pitch of the drill with the anatomic structure, which may lead to anticipation of reaching the outer layer of the bone) and adjust the drilling action to minimize plunging.

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Contributors: Each author contributed to study design, writing the article and approval of the final version for publication. Ms. Khokhotva acquired and analyzed data. Dr. Backstein reviewed the article. Dr. Dubrowski also analyzed data and reviewed the article.

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